

# TEST FOR RADIAL MIXING OF STARS IN M31

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**Abstract:** Effective radial migration and mixing of orbits throughout the stellar disk has been definitively established in the Milky Way, but not in any other galaxy. We show how such radial mixing can be measured (or strongly constrained) in M31 using a combination of existing data and readily available facilities.

**Key words:** galaxies: evolution

## 1. INTRODUCTION: SMOKING GUN

Sellwood & Binney (2002) showed that stars on approximately circular orbits in disk galaxies are expected to move substantially in galactocentric radius under the dynamical influence of transient, non-axisymmetric perturbations in the galactic potential, such as spiral arms or central bars.

There is a variety of ways to test whether such radial mixing is present in the Milky Way (Schönrich & Binney, 2009), with one type of observation acting as a “smoking gun” for this effect: disk stars at the solar circle show a broad range of metallicities at essentially all ages, while present-day gas-phase metallicities show a very narrow dispersion at fixed Galactocentric radius and a radial metallicity gradient (e.g., Deharveng et al. 2000). Together, these two facts are easily explained by radial mixing of orbits and are essentially impossible to explain without radial mixing.

If there is radial mixing, then stars that were born at many different Galactocentric radii (and so in regions with many different gas-phase metallicities due to the observed gas-phase metallicity gradient) would all wind up in the solar neighborhood. Since these stars would originate in regions of both higher and lower metallicity than the solar circle, the solar circle would naturally contain a range of metallicities at each age (except for the very youngest stars that had not yet mixed). Indeed the same would be true (and is observed to be true) at other Galactocentric radii as well. From the present perspective, however, this added evidence is just icing on the cake.

On the other hand, the only way to explain this range of metallicities at fixed age without radial mixing would be to assume that at all times in the past, the dispersion in gas-phase metallicity at fixed Galactocentric radius was of order 0.5 dex, and that this dispersion mysteriously vanished just before our own epoch. Therefore, having analogous information in even one other comparable galaxy would be enlightening.

## 2. DOES M31 HAVE RADIAL MIXING?

One would like to compare the strength of radial mixing in the Milky Way with that in other galaxies. From theory, one expects that in a purely axisymmetric galaxy there would be no radial mixing. By extension, more weakly axisymmetric galaxies should have weaker mixing. M31 is the obvious choice for the first comparison because it is both nearby and appears to have substantially weaker non-axisymmetries than the Milky Way. To our knowledge there have been no direct tests of radial mixing in M31. However, there is one hint that it may be weaker: the bright ring at 10 kpc has an overdensity of stars ranging from 100 Myr to 500 Myr, but the older stars are not noticeably more diffuse in radius (Lewis & Dalcanton, 2015). However, numerical simulations indicate that the effects of radial migration only become manifest after a number of local orbital periods, i.e., beyond 500 Myrs (Minchev et al., 2011).

How strongly radial migration is manifested in a metallicity spread at a given stellar age depends on the radial gradient of the gas metallicity. Yin et al. (2008) have compared gas-phase (or young star) abundance gradients in the Milky Way and M31. There is still considerable debate about the M31 metallicity gradient (Trundle et al., 2002; Sanders et al., 2012): the gradient is presumably somewhat shallower than that of the Milky Way, but a number of tracers indicate a small abundance spread in very young stars at a given radius (Trundle et al., 2002).

Recent observations of the age – velocity dispersion relation in M31’s stellar disk (Dorman et al., 2015) show that this relation differs markedly between the Milky Way and M31: at a given age, M31’s disk stars have a higher velocity dispersion, and their velocity dispersion depends more strongly on age than in the Galaxy. This points toward a different disk formation history in M31, and it would be important to understand whether these differences also translate into a difference in radial migration. Recent numerical simulations suggest that these higher velocity dispersions should make radial migration far less efficient (Vera-Ciro et al., 2014).

### 3. PROPOSED TEST FOR M31 RADIAL MIXING

The “smoking gun” test for effective radial migration and mixing that was outlined in Section 1 can be directly applied to M31. For stars at or above the main-sequence turnoff, ages and metallicities can be measured by combining determinations of the effective temperature  $T_{\text{eff}}$ , luminosity  $L$  and metallicity  $[\text{Fe}/\text{H}]$ . Even with 3-band photometry, one can solve for  $T_{\text{eff}}$ , single-band flux  $F$ , and extinction  $A_V$  under the assumption of known  $[\text{Fe}/\text{H}]$  and extinction-law  $R_V$ . With four bands, one can solve for the extinction law as well. Presently high-resolution 6-band photometry is available from the PHAT survey (Dalcanton et al., 2014). By adding in moderate-resolution (or even low-resolution) spectroscopy, one can solve simultaneously for  $(T_{\text{eff}}, L, [\text{Fe}/\text{H}], A_V, R_V, F)$ . Given that all stars in M31 are at a common (and reasonably well known) distance, one can derive  $L$  from  $(F, T_{\text{eff}}, [\text{Fe}/\text{H}])$ . The viability of such determinations has recently been demonstrated (Dorman et al., 2015).

Moderate-resolution optical spectrographs on large telescopes are already available (e.g., LRIS on Keck or MODS on LBT, Pogge et al. 2010) and even more powerful ones will be available within a few years. With  $[\text{Fe}/\text{H}]$  obtained via low- or moderate-resolution spectroscopy one could therefore measure ages and metallicities on thousands of M31 giants down to several magnitudes below the tip of the red giant branch. If spectroscopy focuses on the rare stars near the tip of the giant branch, not only does it become easier to get sufficient S/N, but source crowding becomes less detrimental.

### 4. FROM EXISTENCE-PROOF TO PROBE

In practice, two tests to quantify the efficacy of radial migration in M31 seem feasible. The first is mapping the metallicity distribution at a given stellar age,  $p([\text{Fe}/\text{H}] | \tau_{\text{age}})$ : in the presence of a spatial  $[\text{Fe}/\text{H}]$  gradient, the dispersion of this distribution should go up with age. The mean of the age-metallicity relation will depend on the radial-age and radial-metallicity gradients.

A second type of test can come from the shape of the metallicity distribution function: in the case of the Milky Way, the metallicity distribution is approximately Gaussian in the solar neighborhood but is skewed both further out and further in (in opposite senses, R. Schönrich 2014, private communication). Detailed modeling of these distributions (including as a function of age) provides a window into the history of our Galaxy. If radial mixing is detected in M31, the next step would be to measure it quantitatively. Modeling of these distributions would then enable a comparison of Milky Way and M31 histories, as well as probing for links between the degree of radial mixing with the strength and form of non-axisymmetries in each galaxy.

Analyzing M31 in this way, would provide the most immediate check on the seemingly high efficacy of radial migration inferred for the Milky Way. M33 is another spiral galaxy, with a far weaker bulge but with a grand

design spiral pattern (Regan & Vogel, 1994), for which multi-band HST imaging exists, and spectroscopy from the tip of the giant branch would provide the metallicities and ages for an analogous test.

With the next generation of telescopes, either ground-based 30m or JWST, galaxies like M81, NGC300, and others may also be available to test whether radial migration is indeed the mechanism that determines the present-day galactocentric radii of individual stars.

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